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SUMMARY

A preliminary analysis of the effectiveness of variable-camber inlet guide vanes in controlling rotor inlet flow parameters with flow change was made. Under study were four basic types of radial distributions of inlet tangential velocity as guide-vane-tip turning was increased to 45°. These distributions were the following functions of radius: inverse (free vortex), constant, linear (wheel-type), and quadratic. The computations were simplified by the assumptions of negligible streamline curvature, no radial-loss gradient terms, and no radial total-temperature gradients in the radial equilibrium calculation.

For the reference rotor inlet conditions chosen, the results show that mass flow can be reduced to 86 percent of the reference value of mass flow without changing the rotor-tip incidence angle. For all types of guide-vane turning, flow control is the most effective if the base or design condition has no guide-vane turning. The maximum flow reductions are attained with the constant, linear, and quadratic tangential velocity distributions with respect to radius at guide-vane-tip turning angles ranging from 20° to 40°. The free-vortex-type turning distribution is the most effective in reducing mass flow at small values of guide-vane-tip turning, but it is limited to low tip turnings by allowable incidence changes at the hub.

For flow rates below about 86 percent of reference mass flow, the rotor-tip incidence must be increased. The results of a study at a highly reduced mass flow show that either axial velocity redistributions or allowable incidence changes greatly restrict the degree to which rotor-tip incidence can be controlled at these reduced flows.

INTRODUCTION

Airbreathing engines for high flight speed and high altitude applications demand high thrust-to-weight ratios and efficient operation over a large range of flight conditions.

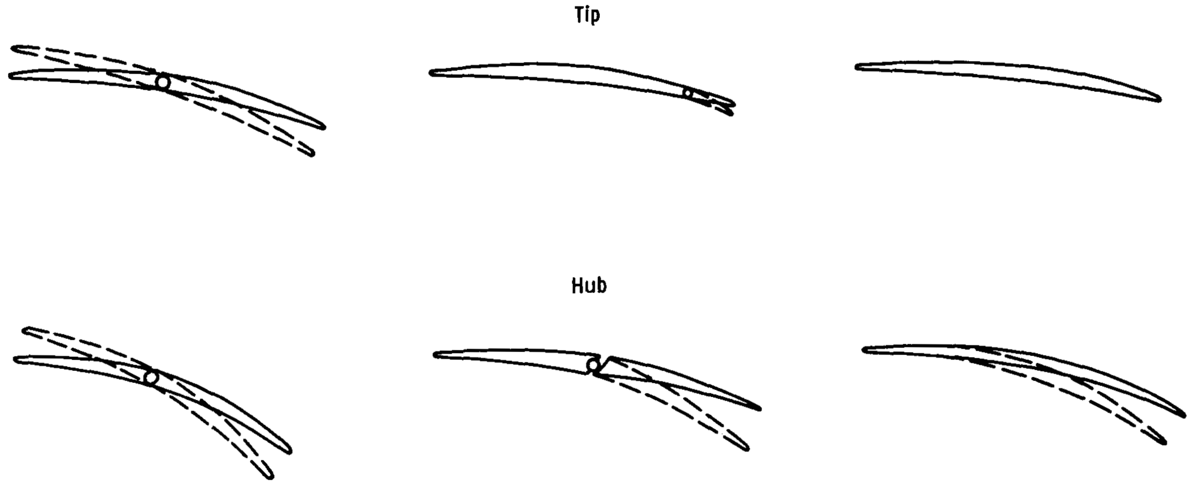
To the compressor designer, these requirements generally mean an increased need for efficient operation over a large range of equivalent flows and blade speeds. To a large extent, improvement of overall compressor range of operation reduces to individual blade row improvements, particularly in the inlet and outlet stages. Stage improvements can, in turn, be made by extending the individual-blade-section stable operating range of incidence by matching or stacking the blade sections for off-design flow incidence angles, or by using methods to reduce the usual individual blade-section incidence-angle change with mass flow. This latter method, or control of flow direction, is the method of primary concern in this study.

To exploit fully the extension of compressor operating range through the control of incidence, variable-camber blade sections would be required along a guide vane and/or stator span. In this report, a preliminary analytical assessment of the ability of variable inlet guide-vane turning to increase the flow range was made. Several basic tangential velocity distributions were studied over a range of flow and guide-vane-tip turning. Throughout the study the blade-tip section was considered to be the most critical, and the calculations and presentations placed particular emphasis on control of flow conditions entering the blade-tip section. Because of the preliminary nature of the study, simplified computational procedures which did not account for effects of streamline curvature and radial gradients of enthalpy and entropy were used.

DEVELOPMENT OF INCIDENCE CONTROL CONCEPTS

Extension of the useful flow range in turbomachinery has always been desirable. In general, however, range extensions are not easily achieved. The study and use of inlet guide vanes to give desired radial distributions of velocity diagrams at the rotor inlet and/or to reduce the rotor-inlet relative Mach numbers (refs. 1 and 2) was an early effort to control flow conditions. With more stringent performance requirements, improvements in the stable efficient operating range of compressors were made by designing inlet guide vanes and stators to be adjustable during operation; that is, solid vanes were rotated about a radial or nearly radial axis as indicated in figure 1(a). Greater mechanical complexity was required to attain this additional freedom to match better the performance of blade sections.

Solid vanes rotated about an axis have the restriction that the flow direction can be optimized at only one radial location. Additional gains in compressor off-design performance could be realized if the air direction entering at all radii could more nearly be optimized. Such an additional degree of freedom could be realized through the use of guide vanes or stators with variable camber along the span. One possible concept of doing this is hinging the blade along a radial axis or possibly a canted axis as indicated



(a) Rotation of blade about a radial axis.

(b) Change of blade section camber by hinging.

(c) Change of blade section camber by distortion.

Figure 1. - Guide vane adjustment concepts.

in figure 1(b). Another is mechanical twist or distortion of the blade as indicated in figure 1(c). An evaluation of feasibility of the additional mechanical complexity of such concepts can be made only after the potential magnitude of the range extension is known. The remainder of the report is the first phase of such an evaluation - that is, an analytical study of the range extension potential of the variable-camber concept.

COMPUTATIONAL AND ANALYSIS METHODS

Computer Program

The computer program used in this analysis was an existing preliminary design or analysis program capable of accommodating performance calculations for a large number of succeeding blade rows. Calculation of the flow conditions was carried out before and after each blade row, and axisymmetric flow conditions were assumed to exist. The form of the radial equilibrium equation solved in the program did not account for effects due to radial velocities, streamline curvature, or radial gradients of entropy. Basic inputs to the program are a tip axial velocity and a radial distribution of tangential velocity which has the general form

$$V_\theta = \frac{B}{r} + C + Dr + Er^2 \tag{1}$$

This simplified program has the advantage that studies of selected parameters over wide

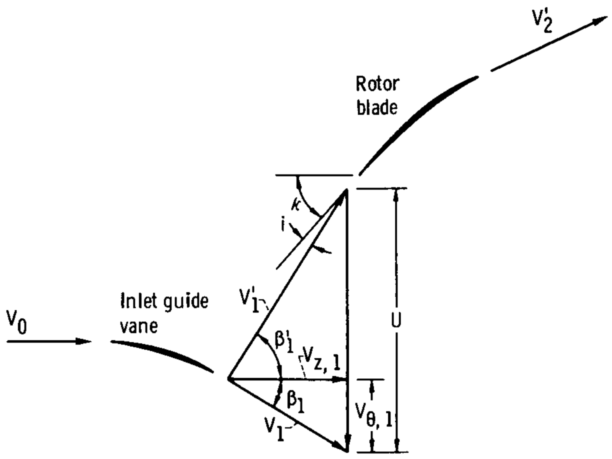


Figure 2. - Rotor-inlet velocity diagram with inlet guide-vane turning.

ranges can be conducted very rapidly. Trends are established and areas of primary interest can then be isolated for more accurate and detailed study.

Specific Analysis and Computational Procedures

This study was specifically concerned with the effects of changing guide-vane turning or guide-vane outlet flow direction on the inlet flow conditions to a succeeding rotor row. Thus, computations were carried out only at an axial station between the guide vane and the rotor. All velocities and angles presented are those associated with the velocity diagram at this station. The relations among flow velocities, flow angles, and rotor-wheel speed are illustrated in the typical diagram shown in figure 2. Throughout this study, rotor-tip speed was held constant. The study was primarily concerned with flow conditions as mass flow was reduced from a reference value; hence, all guide-vane turning is in the direction of rotation.

Guide-vane-tip turning, as such, was not a direct input to the program, but exact values of turning were easily attained through the inputs of a tip axial velocity and a radial distribution of tangential velocity. Four simple, or basic distributions of tangential velocity, in which three of the coefficients of equation (1) were zero, were selected for study. These rotor inlet tangential velocity distributions are identified as follows: inverse, or free vortex, B/r; constant, C; linear or wheel type, Dr; and quadratic, Er^2.

Where applicable, output parameters are shown as changes from reference flow conditions. In this form, the restraints necessary to define the usable flow range could most easily be applied. One of the key blade parameters for measuring the flow range is the incidence angle. Incidence angles cannot be calculated directly without established blade geometry, but incidence angle changes are equal to blade relative flow angle changes, which can be determined from the velocity diagram calculations. In the following discussions, the rotor relative angle changes will be referred to as rotor incidence-angle changes in order to relate flow conditions to blade operating characteristics.

In the formulation of the analysis procedures, the rotor-tip blade section was considered to have the smallest usable incidence range. In evaluating the effectiveness of variable guide-vane control, the first of two analysis approaches was to hold the rotor-tip incidence constant by varying guide-vane-tip turning and to compute the corresponding weight-flow reduction. The second approach was to select arbitrarily a mass flow considerably reduced from the reference value and to compute the required changes in incidence for all blade sections to satisfy the imposed flow rate and tangential velocity distribution. This computational procedure required iterative axial velocity changes to satisfy mass-flow conditions. The procedure significantly increased the complexity and time to obtain output data. Application of the computer procedures to the two approaches are discussed in more detail in the following sections.

Constant-rotor-tip-incidence-angle studies. - The effects of each of the four inlet guide-vane types were investigated with rotor-tip incidence angle i_t kept constant at its reference value. Thus, the tip relative velocity triangles of the velocity diagram for each of the guide-vane types were similar. For given values of guide-vane-tip turning β_t, the tip tangential velocity was calculated from

$$V_{\theta,t} = \frac{U_t}{1 + \dfrac{\tan \beta_t'}{\tan \beta_t}} \tag{2}$$

where β_t' and U_t are reference values. The guide-vane-tip turning β_t was varied in 15° intervals to a maximum of 45°. Once $V_{\theta,t}$ is determined, the constants B, C, D, and E and $V_{z,t}$ are obtained from

$$B = r_t V_{\theta,t}$$

$$C = V_{\theta,t}$$

$$D = \frac{V_{\theta,t}}{r_t}$$

$$E = \frac{V_{\theta,t}}{r_t^2}$$

and

$$V_{z,t} = V_{\theta,t} \cot \beta_t$$

Reduced-mass-flow studies. - In these studies, the requirement that the rotor-tip incidence angle remain constant was removed and, instead, a rather arbitrarily chosen mass flow equal to 67.6 percent of the reference value was specified. Since the program was set up to input $V_{z,t}$ rather than mass flow, it was necessary to estimate and adjust $V_{z,t}$ in an iteration process to match the desired mass flow. The velocity $V_{z,t}$ was iterated until the resulting mass flow was within ±0.2 percent of the selected value of 67.6 percent of the reference value. For each new value of $V_{z,t}$, a value of $V_{\theta,t}$ and constants B, C, D, or E for the tangential velocity distribution equation were calculated to maintain the same 15° intervals in the guide-vane-tip turning angle.

Rotor Inlet Conditions at Reference Flow

To provide quantitative results, a base set of inlet flow conditions were selected for a rotor without inlet guide vanes ($V_{\theta} = 0$). The flow conditions are as follows:

Inlet axial velocity, V_z, ft/sec	439
Blade-tip speed, U_t, ft/sec	805
Hub-tip radius ratio, r_h/r_t	0.4

The axial velocity was assumed constant across the passage. These values result in relative flow angles of 61.4° at the tip and 36.3° at the hub. At standard temperature and pressure, these velocities resulted in an inlet absolute Mach number and tip relative Mach number of 0.40 and 0.83, respectively. For conventional stages, these values represent part speed conditions or the region where flow range extention is most needed.

Incidence-Angle Range Restraints

A blade is designed as a number of radially stacked sections. Each individual blade section operates over a range of incidence angles for which the loss incurred in the flow around the blade section is relatively small. If the blade section is forced to operate at incidence angles outside the low-loss range, the losses generally rise very rapidly and the blade section may stall. Good efficiency for the complete blade is realized when all the individual blade sections are operated in the low-loss incidence range. The objective of the variable-camber guide vane is to alter the direction of air entering the rotor as flow is reduced to aid in maintaining the incidence angles at all blade sections within their individual low-loss ranges. Throughout this study the stable operating flow range of the blade row is considered to be reached whenever any blade section reaches a selected limiting incidence change, either positive or negative, from optimum. These limits are considered to define the usable incidence range for analysis purposes whether or not stall or choke conditions are actually reached, since the high-loss regions near stall and choke are almost equally undesirable.

A survey of two-dimensional cascade and single-stage rotor data, such as presented in references 3 to 6, shows that the low-loss incidence ranges generally are $\pm 2^{\circ}$ to $\pm 6^{\circ}$ from the reference value of incidence in the tip region where the highest relative Mach numbers and stagger angles occur. Over the rest of the blade the incidence ranges generally are $\pm 6^{\circ}$ to $\pm 10^{\circ}$ from the reference values of incidences. The ranges of values appear because the low-loss range of incidence angle applicable to a given blade section generally increases as rotor relative inlet Mach number, blade loading, and blade stagger decrease. Such considerations make the selection of unique-blade-section incidence-angle restraints for all applications impossible. For a given application, it is necessary to weigh the previously mentioned factors and to select values of appropriate limiting Δi to define the estimated flow range. For this investigation, values of Δi were chosen as $\pm 6^{\circ}$ at the tip and $\pm 10^{\circ}$ at the hub for the reference conditions selected. If desired, however, other limits can be selected and easily applied on the curves presented in the next section.

RESULTS AND DISCUSSION

Constant-Rotor-Tip-Incidence-Angle Study

The computed results for a constant rotor-tip incidence angle are introduced in figure 3 by showing radial distribution of change in incidence angle for the four tangential velocity distributions at one value of guide-vane-tip turning angle. The dotted line is a linear application of the incidence change limitations selected earlier from stall considerations. The curves at this one value of guide-vane-tip turning illustrate the general form of the change in incidence distributions. Toward the hub of the type B/r distribution, incidence changes indicate rapid movement to a deeply stalled condition. Types C and Dr with guide-vane-tip turning angles up to 30° also have maximum incidence changes at the hub, but the rate of incidence change in approaching the hub and the portion of blade in negative stall becomes progressively less than with type B/r. The maximum incidence change for type Er^2 does not occur at the hub, but the maximum incidence change of 2° is relatively small so that the hub value still approximately represents the maximum magnitude of the incidence change. At other values of tip turning, the curves hold the same general form. Note that for the incidence limit criterion

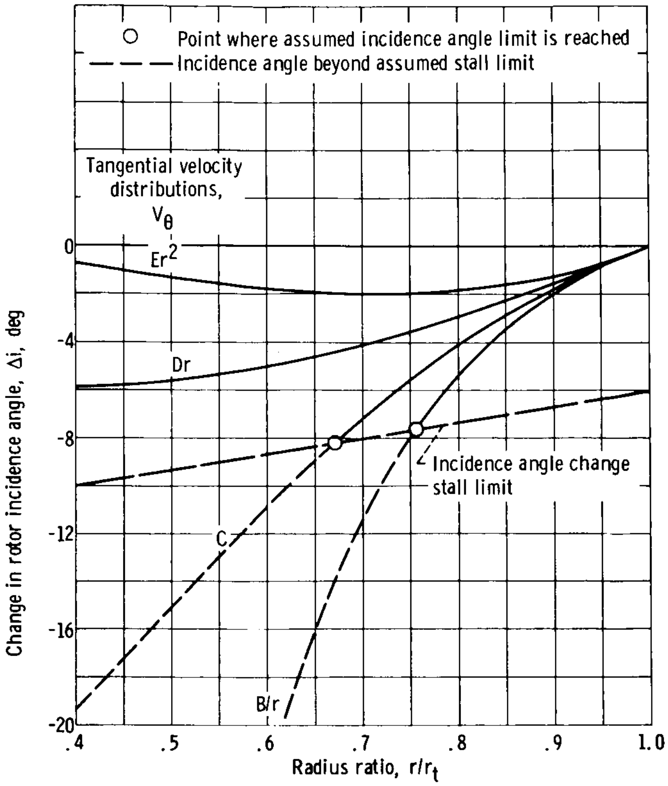


Figure 3. - Radial distribution of rotor incidence angle change. Guide-vane-tip turning, 30°.

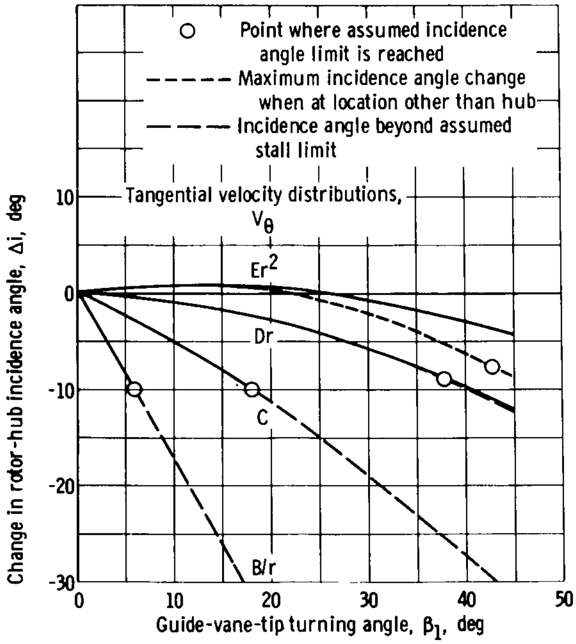


Figure 4. - Change in rotor hub incidence angle as function of guide-vane-tip turning angle with rotor-tip incidence angle held constant.

shown, the hub sections of types Dr and Er^2 will not reach the limit first as the tip turning angle is increased.

In figure 4 the rotor-hub incidence changes are shown as functions of guide-vane turning at the tip. For the type Er^2 tangential velocity distribution, the maximum incidence changes are also shown as a dashed line where they are different from the hub values. The incidence change stall limits selected previously are indicated as small circles on the curves. The dashed extension to the curves means that increasing portions of the blade span will be operating in the stalled condition. The figure shows that the stall limits hold the type B/r guide-vane-tip turning angle to 6° or less. These stall range considerations also limit the guide-vane-tip turning of the other vane types, but the limits occur at succeedingly higher guide-vane-tip turning angles in moving toward the Er^2 type. With the linear stall criterion indicated in figure 3, the Dr and Er^2 types first reach the stall limit at a blade section above the hub.

The reductions of mass flow that accompany the increased guide-vane-tip turning for each type of V_θ distribution are shown in figure 5. The curves of figure 5 show that the largest mass-flow reduction is made with the first increment of guide-vane-tip turning. If guide-vane turning of one of the types of V_θ distribution under study already exists, however, the data shown in figure 5 can be used to determine the effectiveness of greater guide-vane turning. The existing value of guide-vane-tip turning should be located on figure 5 and changes measured from it as a reference. Note that it is necessary to use the same V_θ distribution in moving to a new value of guide-vane-tip turning angle when the curves are used in this manner because the other types do not pass through the new reference point. The guide-vane turnings shown are of the more general form $V_\theta = Cr^n$ where $n = -1, 0, 1,$ and 2. If the guide-vane turning of interest can be approximated by $V_\theta = Cr^n$, where n is between -1 and 2, the analysis can be performed on an interpolated curve provided the preceding conditions are observed. The figure, however, shows that limited gains are available when existing guide-vane turning in the direction of rotation is the reference point; that is, this method of flow control is most effective if the base or design condition has no guide-vane turning.

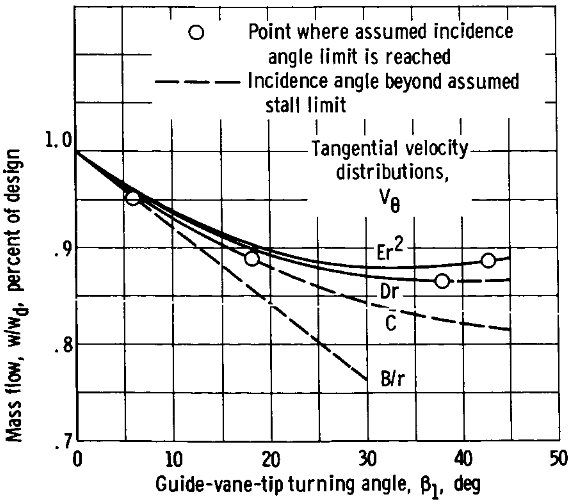


Figure 5. - Change in mass flow as function of guide-vane-tip turning with rotor-tip incidence angle held constant.

As in the other figures, flows at which the incidence angle change for any blade section exceeds the selected limiting values are shown as dashed lines in figure 5. Such considerations seriously limit the potential

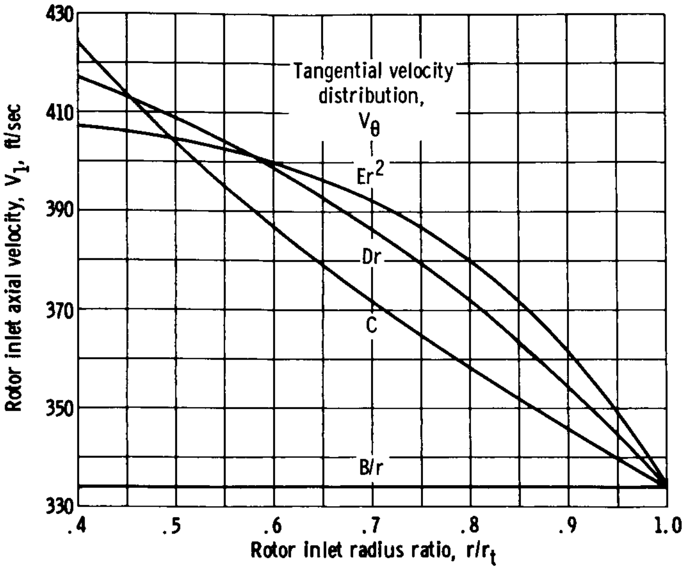


Figure 6. - Rotor inlet axial velocity profiles. Guide-vane-tip turning, 30°.

effectiveness of the type B/r tangential velocity distribution in reducing mass flow. The potential effectiveness of type C in reducing mass flow is also somewhat impaired by the allowable incidence consideration, but the Dr and Er^2 types are virtually unaffected.

At the higher guide-vane-tip turnings shown in figure 5, the Dr and Er^2 types, in fact, have a minimum mass flow of 86 to 88 percent of the reference value even though the allowable incidence limits are not reached. This is caused by axial velocity redistribution toward the hub as shown in figure 6 for the case of 30^o of guide-vane-tip turning. The redistribution increases with the magnitude of the tip V_θ or with guide-vane-tip turning until a point is reached where the axial velocity redistribution and the associated density changes cause the mass flow to increase again even though the tip axial velocity is still being reduced.

With consideration of both the minimum mass flow and stall range of incidence limitations, there appears to be little or no advantage in using guide-vane-tip turning angles greater than about 40^o for the rotor relative tip angle used in this analysis. When the tip incidence is held constant, the type B/r tangential velocity distribution is limited to only a 5-percent mass-flow reduction at about a 6^o guide-vane-tip turning angle by the hub stall considerations. For the same restraining conditions on the other types of V_θ distribution, the maximum flow reductions from the axial inlet condition are about 10 to 14 percent with about 20^o to 40^o of guide-vane-tip turning.

The effect of guide-vane turning on relative and absolute Mach numbers is shown in figures 7 and 8. Figure 7 shows that the tip relative Mach number is significantly and progressively reduced with increased guide-vane-tip turning. Note, however, that the circles on the figure indicate the guide-vane-tip turning angles at which the incidence

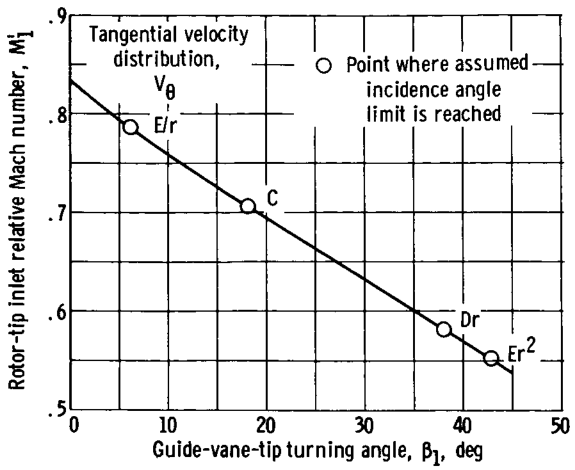
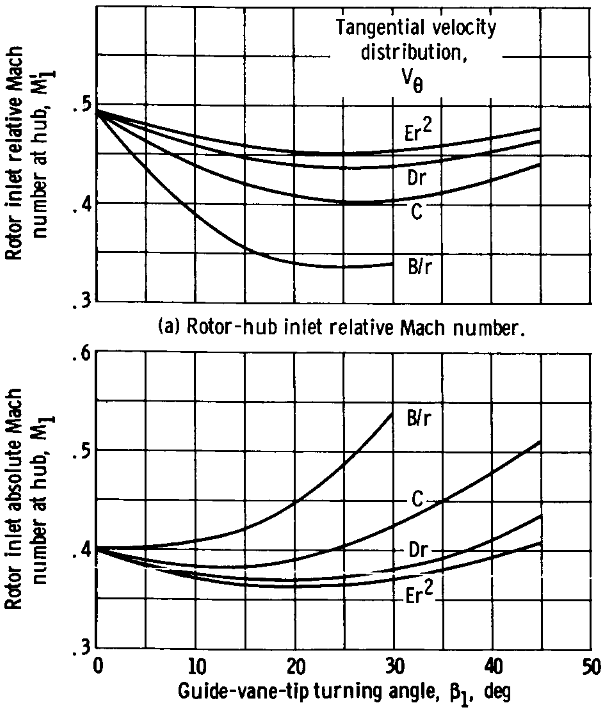


Figure 7. - Variation of rotor-tip inlet relative Mach number with guide-vane-tip turning angle.



(a) Rotor-hub inlet relative Mach number.

(b) Rotor-hub inlet absolute Mach number.

Figure 8. - Variation of rotor-hub inlet Mach numbers with guide-vane-tip turning angle.

change limitation was first reached. Since the general trend of off-design incidence range is to increase as relative Mach number is reduced, the reduction of the tip relative Mach number may be the primary purpose of the guide vane in some cases. Types Dr or Er^2 would most likely be used for this purpose since they permit operation to the highest guide-vane-tip turning angles, and thus the largest relative Mach number reductions. The hub relative Mach numbers shown in figure 8(a) and the absolute hub Mach numbers shown in figure 8(b) do not change nearly as much with change in guide-vane-tip turning as did the relative tip Mach number.

Throughout the presentation of these results, it has been presumed that the variable-camber guide vanes needed to produce the computed radial distributions of turning are mechanically feasible. In figure 9 some preliminary consideration is given to the guide-vane geometry by relating the fluid turning angle at the hub to the fluid turning angle at the tip. As a first approximation, the guide-vane camber angles can be assumed to be equal to fluid turning angle. Thus, figure 9 shows the approximate blade section camber that would be required at the hub and tip of the blade for each flow condition investigated. The dashed line indicates equal hub and tip flow turning. The significance of this line is that it represents a configuration of low blade twist, since changes in incidence and deviation angles are the only factors affecting blade twist. Distributions

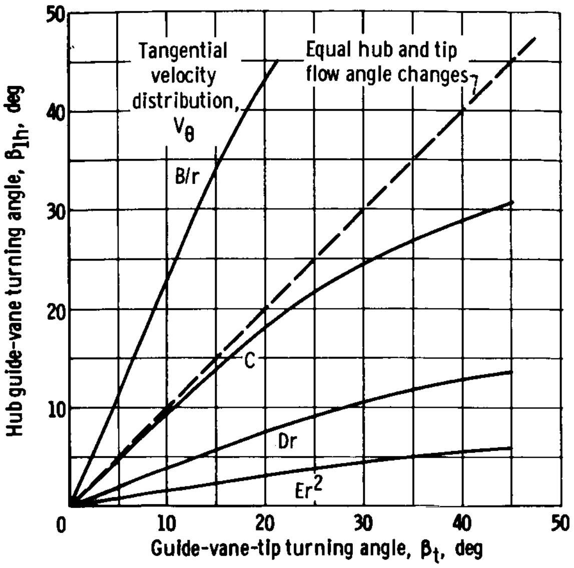


Figure 9. - Hub guide-vane turning angle as function of guide-vane-tip turning angle with rotor-tip incidence angle held constant.

B/r and Er^2 required the greatest blade twist and may be the most difficult to design mechanically.

Reduced-Mass-Flow Study

In this section, results are presented for the second analytical approach in which tip incidence is varied for a constant mass flow. The weight flow was held constant at a very low mass flow rate, 67.6 percent of the reference value, as combinations of guide-vane-tip turning and tangential velocity distributions were investigated for their ability to reduce rotor incidence changes at all blade sections. The first of these studies are presented in figure 10 which shows radial distributions of the change of rotor incidence angle from the reference axial inlet condition for each of the four V_θ distributions at a guide-vane-tip turning angle of 30^o. For comparison, the radial distributions of incidence change that would result at the reduced flow with no guide vanes are also presented. The associated axial velocity distributions are shown in figure 11.

The type B/r guide vane is the most effective in reducing the change in tip incidence angle, but the change in hub incidence far exceeds the 10^o allowable incidence limitation. None of the other types are within the most liberal tip incidence stall range limit of 6^o.

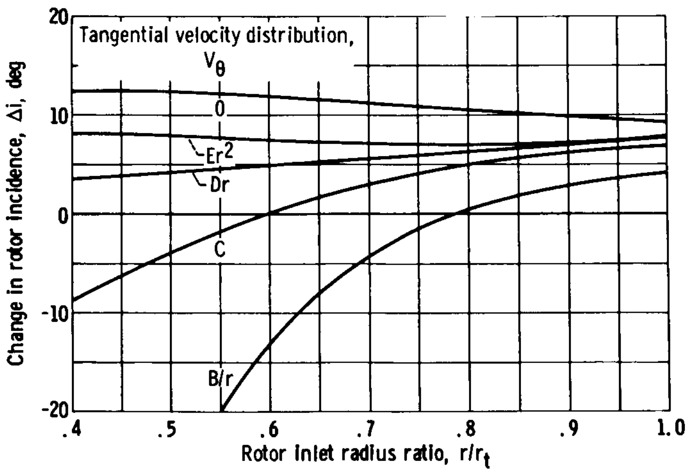


Figure 10. - Effectiveness of guide vanes with 30° tip turning in reducing change of rotor incidence angle for mass-flow reduction from 100 to 67.6 percent of design.

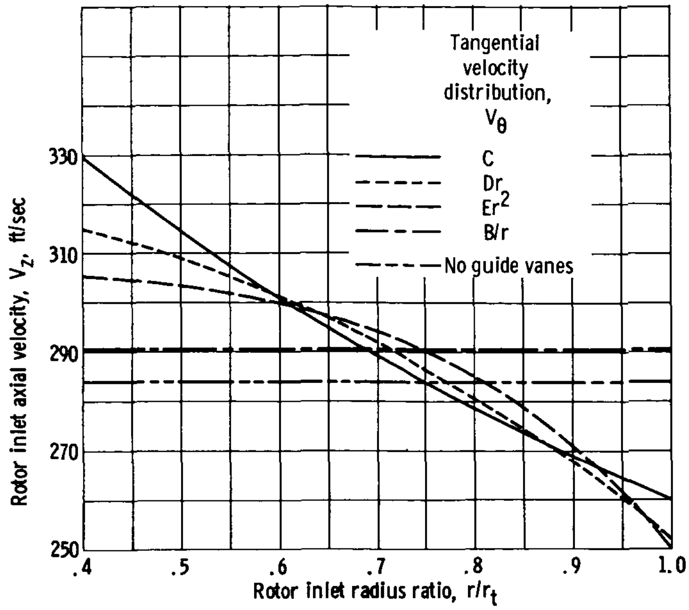
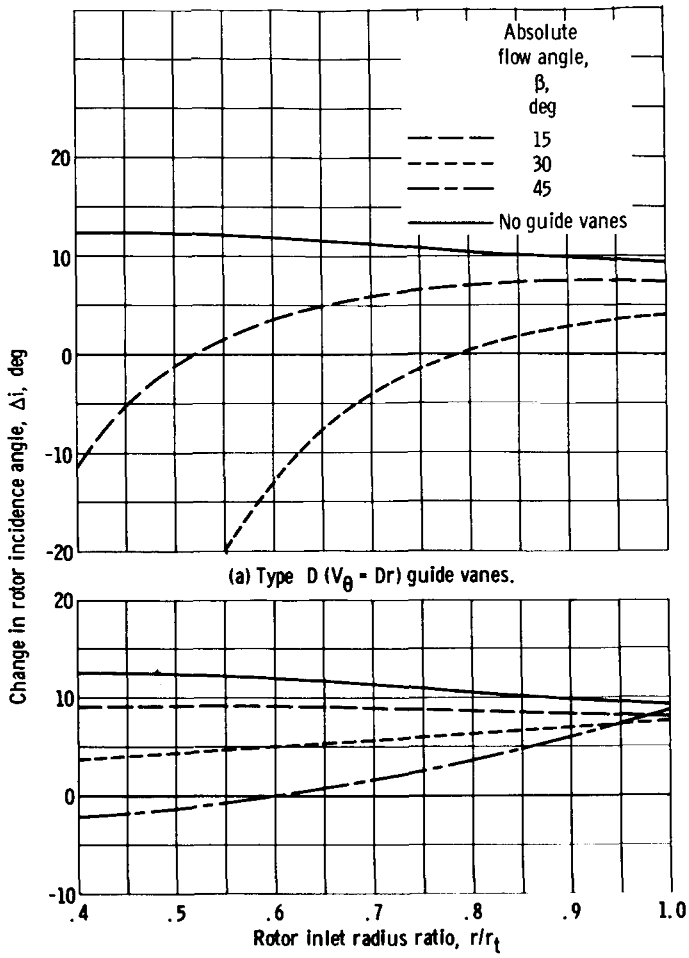


Figure 11. - Comparison of rotor inlet axial velocity profiles behind 30° tip-turning guide vanes of 67.6-percent of design mass flow.

Hence, none of the 30° guide-vane-tip-turning configurations shown are likely to give acceptable performance at flow reductions to 67.6 percent of the reference value. However, the plots do achieve the major purpose of this portion of the analysis which is to illustrate the relative merits of the various tangential velocity distributions. The trend shown would be expected to apply at other selected weight flows.

Of equal interest is a comparison of the Δi's for cases with guide-vane turning and no guide-vane turning for the same mass-flow change. As long as Δi with guide-vane turning is less than that with no guide-vane turning there is some range extension available. In the tip region, however, the difference is relatively small and the degree of tip incidence control with a change in the type of guide-vane turning distribution is low. One reason for this is the axial velocity redistribution (fig. 11). In the tip region, the reduction of axial velocity with increased guide-vane-tip turning tends to keep the relative flow angle nearly constant. However, in the hub region the increased axial velocity and the increased tangential velocity cause angle changes in the same direction with the result that large incidence changes in the negative direction occur. A second reason for the low relative angle sensitivity of the tip is associated with the magnitude of the base relative flow angle. If the velocity diagrams are studied, such as the one in figure 2 (p. 4), it can be seen that a given change in guide-vane turning or axial velocity will cause a smaller change in relative flow angle as the magnitude of the base relative flow angle is increased. Thus, in the tip region where the highest level of relative flow angle generally exists, relative angle changes are lower than those which occur at lower radii blade sections. This latter effect is demonstrated in figure 11 by the radial distribution of



(a) Type D (V_θ = Dr) guide vanes.

(b) Type B (V_θ = B/r) guide vanes.

Figure 12. - Effect of guide-vane distribution constants in reducing rotor-incidence-angle changes for mass-flow change from 100 to 67.6 percent of design.

change of rotor incidence angle with weight flow for the case of no inlet guide vanes. For this case, the same change of axial velocity is impressed on the hub and tip velocity diagrams. In the tip region the change in incidence angle (or relative flow angle) is 9.2° compared with a hub element change of 12.3°.

In the previous discussion only a 30° guide-vane-tip turning was considered. Types Dr and B/r, because of their better tip conditions, were selected for further study at other values of guide-vane-tip turning to seek a more effective guide vane at this reduced mass flow of 0.676, the weight-flow reference. The results are shown in figure 12. At a 15° guide-vane-tip turning, the B/r type is nearly within the hub incidence range, but the tip incidence is the same range as the 30° Dr and Er^2 types in figure 10 (p. 12). The 30° Dr and Er^2 types, however, have a better overall incidence distribution. Figure 12(b) shows that the lowest tip incidence of the type Dr tangential velocity distribution occurs with a guide-vane-tip turning the neighborhood of 30°. Thus, there appears to be very little incidence improvement available at this low flow by operating at other than 30° guide-vane-tip turning.

SUMMARY OF RESULTS

A preliminary assessment of the potential of variable guide-vane turning to extend flow range was performed by means of a simplified analytical velocity diagram study by using guide-vane whirl velocity distributions of the general form $V_\theta = Cr^n$ where n values from -1 (free vortex) to 2 (quadratic) were investigated. Evaluations of the flow control effectiveness of variable geometry guide vanes were made by varying guide-vane turning while (1) holding rotor-tip incidence angle constant, and (2) holding mass flow constant.

The results of the constant-tip-incidence-angle study show that with all types of guide-vane turning the largest mass flow reduction is made with the first increment of guide-vane turning from the axial direction. Thus, this method of flow control is most effective if the base or design condition has no guide-vane turning. With the free-vortex distribution, the hub section incidence angle quickly reached the selected limiting incidence change of 10° for a modest 5-percent reduction of mass flow. The other types permitted maximum mass flow reductions of 11 to 14 percent from the reference value for guide-vane-tip turning of 20° to 40°. The $V_\theta = Cr$ and $V_\theta = Cr^2$ types allow the greatest reduction of rotor inlet relative Mach number in the tip region; however, no attempt was made to include the added effect on flow range. Without consideration of incidence and deviation angles, the $V_\theta = C$ distribution appears to require the smallest change of guide-vane camber along the blade span and, thus, ought to be the easiest to build.

In the second part of the study, a weight flow of 67.6 percent of the reference value distribution was chosen and held constant while different combinations of guide-vane-tip turning and tangential velocity distributions were investigated for the ability to reduce rotor incidence changes at all blade sections. The analytical results indicated that, within the assumed limitations on incidence angle change, none of the V_θ distributions would provide efficient operation at all blade sections at this large reduction of mass flow. However, the radial distributions presented show that guide vanes definitely can reduce the incidence changes, and these distributions are believed to be indicative of those that would be computed at any reduction of flow below the reference value.

CONCLUDING REMARKS

The analytical results of this study show the potential flow range improvement that may be expected with variable geometry inlet guide vanes. The results show some of the general parametric trends and also indicate the turning angle ranges and blade types for which it should be the most profitable to concentrate future efforts. More refined studies could include more complex V_θ distributions with added attention given to the values chosen for allowable incidence range. In a design study for a given application, the effects of streamline curvature and radial entropy gradients should be considered because they affect the radial distribution of axial velocity. In general, the changes that the inclusion of these additional terms impose upon the axial velocity are quite similar for the various vane types in a given annulus geometry. Thus, it is not expected that the inclusion of these effects will change the relative merits of the various types. Also, the additional mechanical complexity and methods of control must be weighed against the aerodynamic improvements. Such considerations could make some of the blade types impractical.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 19, 1966,
720-03-01-48-22.

APPENDIX - SYMBOLS

B constant factor for inverse radial distribution of tangential velocity (see eq. (1)), ft^2/sec

C constant factor for constant radial distribution of tangential velocity (see eq. (1)), ft/sec

D constant factor for linear radial distribution of tangential velocity (see eq. (1)), 1/sec

E constant factor for quadratic radial distribution of tangential velocity (see eq. (1)), 1/ft-sec

i rotor incidence angle, deg

Δi change of incidence from reference value at axial inlet flow, deg

M Mach number

M' relative Mach number

r radius, in.

U blade speed, ft/sec

V absolute velocity, ft/sec

V' relative velocity, ft/sec

β absolute flow angle, deg

β' relative flow angle, deg

κ_i rotor inlet blade angle, deg

Subscripts:

h hub

t tip

z axial

θ tangential component

0 guide vane inlet

1 rotor inlet

2 rotor outlet

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